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Differences in Gait Between Children With and Without Developmental Coordination Disorder

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In the present study the walking pattern of 10 children with developmental coordination disorder (DCD) was investigated and compared to that of 10 typically developing, matched control children. All children walked at a similar velocity that was scaled to the length of the leg on a motor-driven treadmill. Three-dimensional kinematics were recorded with a motion capture digital camera system. The spatiotemporal parameters of the gait pattern revealed that children with DCD walked with shorter steps and at a higher frequency than the typically developing children. In addition, the children with DCD exhibited a body configuration that demonstrated increased trunk inclination during the entire gait cycle and enhanced during the entire gait cycle. At toe-off a less pronounced plantar flexion of the ankle was observed in children with DCD. In conclusion, it appeared that children with DCD make adaptations to their gait pattern on a treadmill to compensate for problems with neuromuscular and/or balance control. These adaptations seem to result in a safer walking strategy where the compromise between equilibrium and propulsion is different compared to typically developing children.

Key Words: locomotion, clumsiness, postural control, adaptation

Locomotion is fundamental for optimal child development. The ability to smoothly and adequately navigate through the environment enables the child to interact with the environment and to gain different kinds of experiences. Locomotion is not only a prerequisite to fulfill primary needs like the search for food (Patla, 1997), it is also a key factor from a psychosocial point of view, since it facilitates social interaction and participation in sports and games. It may be clear that children with movement

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disorders which involve problems with locomotor activity therefore are put at a disadvantage with regard to their development. In this respect, cerebral palsy (CP) has been the subject of a considerable amount of research (e.g., Damiano & Abel, 1996; Massaad, Dierick, van den Hecke, & Detrembleur, 2004; Sutherland, 1978). Less attention has been paid to milder movement disorders, such as developmental coordination disorder (DCD).

The diagnosis of DCD refers to children with movement disorders which are characterized by coordination difficulties in several gross and/or fine motor tasks. These difficulties hamper the children significantly to fulfill a broad range of activities of daily living. The children have a normal intelligence and in contrast with, for example, CP or muscular dystrophy, an overt neurological disease or any other medical condition is absent. Despite the strict criteria formulated by the American Psychiatric Association (APA) in the Diagnostic and Statistical Manual of Mental Disorders (DSM IV; APA, 1994) some children with DCD exhibit motor behavior that is reflective for minor neurological dysfunctions such as difficulties with the regulation of muscle tone or an increased knee tendon reflex in the absence of hard neurological evidence (Hadders-Algra, 2000 & 2002; Lundy-Ekman, Ivry, Keele, & Woollacott, 1991).

According to Patla and co-workers (1991) successful locomotion requires (1) producing a locomotor pattern for supporting the body against gravity and propelling it forward, while (2) maintaining the body in balance, and (3) adapting the pattern to meet environmental demands. The bipedal walking pattern that humans have adopted over time constitutes an elegant way to meet these requirements in an efficient and economic way. Several findings with respect to motor control in children with DCD however, indicate that they could have problems meeting (some of) these constraints. A first potential limitation is related to neuromuscular control in children with DCD. Raynor (2001) observed decreased muscular strength and power in children with DCD, accompanied by increased levels of co-activation in a unilateral knee flexion and extension task. Similar neuromuscular problems, indicating difficulties with the selective muscle control necessary for rhythmic coordination, were found in a unilateral tapping task by Lundy-Ekman et al. (1991). Likewise Volman and Geuze (1998) showed that these rhythmic coordination difficulties of children with DCD are not restricted to the control of unilateral tapping. By means of a bimanual flexion-extension paradigm they found that relative phase stability of children with DCD was less stable than in controls. Further investigation is warranted to examine whether similar interlimb coordination problems are present in the lower limbs. However, needless to say, if that is the case, it might be harmful for establishing a propulsive bilateral gait pattern that supports the body against gravity.

Second, with regard to balance various researchers agree that children with DCD show deficits in the control of posture as observed in the increased levels of postural sway during quiet stance (Geuze, 2003; Przysucha & Taylor, 2004; Wann, Mon-Williams, & Rushton, 1998). Data on postural control collected recently in our own lab nicely showed that the increased levels of postural sway of children with DCD are accompanied by a greater dependency on vision and difficulties in the re-weighting of the sensory modalities in response to environmental constraints (Deconinck, De Clercq, Van Coster, Savelsbergh, Cambier, & Lenoir, submitted). From studies where upright stance was perturbed by means of a sudden displacement of a moveable platform it was concluded that the balance recovery strategy of children with DCD was different (Williams, 2002). Their strategy was characterized by a top-down muscular activation pattern compared to the distal-proximal pattern displayed by children without DCD, which was argued to be more efficient. In stance the projection of the center of mass has to be kept within the borders of the base of support to maintain balance. For locomotor balance, however, one must achieve a compromise between the forward propulsion of the body, which involves a highly destabilizing force, and the need to maintain overall stability (Winter, 1995). Taking into account this complexity with respect to the control of posture during locomotion it can be hypothesized that the balance problems experienced by children with DCD might be a limiting factor for their locomotor activity.

So far, descriptions of the gait pattern of children with DCD are limited to some qualitative observations. Larkin and Hoare (1991) have noted for example poor head control, bent arms in a guard position, jerky limb to limb transitions, excessive hip flexion, pronounced asymmetry, wide base of support, short steps, foot strike with flat foot and toe-walking. In an attempt to quantify the gait pattern of children with DCD, Woodruff, Bothwell-Myers, Tingley, and Albert (2002) developed an index of walking performance. This index is based on a comparison of four spatio-temporal gait parameters (time of opposite toe-off, single stance time, total stance time, and step length) with reference parameters of the San Diego database (Sutherland, Olshen, Biden, & Wyatt, 1988). From their calculations, Woodruff et al. concluded that the walking pattern of six out of seven children with DCD indeed was atypical. This one-dimensional measure of walking performance is useful for classifying and evaluating gait performance in clinical practice; however, it does not explain the nature or source of atypical gait. In addition, comparison of gait variables with a reference population without controlling for stature (or leg length) and body weight might obscure deviations and lead to imprudent conclusions, since the walking pattern is highly dependent on anthropometrical characteristics (Hof, 1996; Stansfield et al., 2003). Therefore, to gain insight into the gait pattern of children with DCD, more detailed and quantitative data are needed.

The present study investigates whether the previous (qualitative) findings of atypical walking in children with DCD could be confirmed by detailed, kinematic analysis of the walking pattern and by a comparison with rigorously matched control children. The results will add quantitative data to the existing qualitative descriptions and as such extend the picture of the disorder. It is hypothesized that the postural control as well as the interlimb coordination difficulties of children with DCD, as found in previous studies, will induce significant adaptations to the gait pattern. Problems with posture and/or neuromuscular control might force children with DCD to accommodate the specific relation between balance and propulsion during locomotion, resulting in a different gait pattern with regard to spatiotemporal control of the gait cycle as well as to joint kinematics.

Method

Participants

The children with DCD were recruited from the patient files of 35 collaborating psychomotor therapists. By scanning the personal file of each child it was verified whether the children met the DSM IV criteria for DCD (APA, 1994). Before being referred for (psychomotor) therapy all children were subjected to an extensive neurological examination to preclude neuromuscular or neurological dysfunctions. This examination included assessment of (postural and peripheral) muscle tone, muscle force, peripheral reflexes, balance, the quality of voluntary movements, and the integrity of the cranial nerves. In addition, gestation of all children was normal and without complications and children were born at term without unfavorable obstetrical conditions. Further, the children were determined to be mentally healthy, and, based on their poor scores on the Movement Assessment Battery for Children (MABC; Henderson & Sugden, 1992), they were referred for therapy. If at the time of the current study their score on the MABC was still below the 15th percentile, the children were invited to participate. By means of this selection procedure, 10 children (9 boys and 1girl) with a mean age of 7.4 years (*SD* = 0.86), were recruited. Four participants scored below percentile 5 and the remaining six between percentile 5 and 15 (range: 1–12). A closer look at the scores on the three MABC clusters (fine motor skills, ball handling skills, and balance skills) indicated that 4 children scored below percentile 5 for fine motor, manipulative skills while 6 scored between percentile 5 and 15. The same was true for ball handling, but for balance all children scored above the 15th percentile. The latter, however, did not imply that the children with DCD did not experience problems with the control of posture, since a related study revealed that all these children exhibited increased levels of postural sway as assessed with a Clinical Test of Sensory Interaction on Balance (Deconinck et al., submitted).

All children completed a physical activity questionnaire with the assistance of at least one of their parents. This questionnaire was developed to determine the degree and nature of the physical activity of the child. For the recruitment of children for the control group the same questionnaire was distributed to the 6-8 year-old children of two primary schools (*N* = 300) in the neighborhood of the Department for Movement and Sports Sciences. After a rigorous matching procedure, taking into account sex, age, intelligence, stature, body weight, and degree and nature of daily physical activity a group of 10 typically developing (TD) children was selected to serve as a control group. The TD children were free from medical conditions or behavioral disorders. Their score on the MABC was higher than percentile 33. Details of the demographic data of both groups and inferential statistics are given in Table 1. The protocol of this study was in accordance with the guidelines of the Declaration of Helsinki and approved by the Ethical Committee of Ghent University. All parents gave their written informed consent prior to participation and the children assented to the testing.

Instrumentation

Children walked barefoot on a motor-driven treadmill (STAR model TM505, 1HP) at an imposed velocity which was scaled to the length of the leg according to the Froude number (Fr).

$$Fr = \frac{v^2}{g.L}$$

Table 1 Means, Standard Deviation, and *t*-Test Values Relative to Demographic Data of Boys With and Without DCD

Variable	Children with DCD *M*	Children with DCD *SD*	Children without DCD *M*	Children without DCD *SD*	*t*(9)
Age (years)	7.4	0.86	7.5	0.85	0.408
Stature (m)	1.28	0.070	1.31	0.051	1.130
Leg length (m)	0.59	0.057	0.59	0.037	0.070
Body weight (kg)	25.3	4.11	28.0	4.35	1.427
PA school (hr/wk)	3.5	1.65	3.7	1.46	0.275
PA leisure (hr/wk)	2.0	1.48	2.5	1.84	0.687
Math grade (%)	88	8.3	91	7.2	1.393
MABC percentile	7.3	4.50	69.1	22.17	8.638*

Note. PA school = amount of physical activity at school in hours per week (i.e., sum of the hours of physical education and playground activities). PA leisure = amount of regular physical activity in leisure time in hours per week. Intelligence was matched by means of the math grade. It has been shown that this value correlates well with the total IQ (Brusselmans-Dehairs et al., 2002).* $p < .001$

where v is the walking velocity; g is the acceleration due to gravity and L is the leg length. Walking at an equal Froude number results in *dynamic similarity* where lengths, times, frequencies, velocities, and forces are proportional to each other (Zatsiorsky, Werner, & Kaimin, 1994). The Froude number was set at 0.15, which resulted in a mean walking velocity of 0.85 m/s on average for both groups.

Three-dimensional kinematic data were collected with an eight ProReflex camera system (Qualisys, Gothenburg, Sweden). Spherical markers 6 mm in diameter were placed bilaterally on seven bony landmarks: the caput of the fifth metatarsal, malleolus lateralis (ankle), epicondylus lateralis femoris (knee), trochanter major femoris (hip), acromion (shoulder), epicondylus lateralis of the humerus (elbow), and the processus styloideus of the ulna (wrist).

Procedure

Three to four weeks before the test the children were invited for a practice and habituation session which was identical to the actual experiment. This first session started with a short acquaintance with the three testers, the lab, and the equipment. Next, the children were tested with the MABC.

All participants were naïve to treadmill walking and before recordings the children were given a practice period of approximately 10 min to become familiar with the treadmill. According to Wall and Charteris (1981) habituation mainly occurs during the first minute of locomotion. In Stolze et al. (1997) a similar period of time appeared sufficient for children to produce a stable walking pattern. Before the child took his or her place on the treadmill, one of the experimenters demonstrated the whole course of the experiment. Meanwhile, he instructed the children to keep walking at a steady-state velocity in between the two lines of tape fixed to the treadmill frame while looking ahead. Subsequently, the child mounted the treadmill, holding the hand of the experimenter at his or her right side. The velocity of the walking belt was gradually increased to the desired scaled velocity by the tester while the child was encouraged to initiate stepping and instructed to look ahead. During the first 2 min, the child walked hand in hand with a tester at the right side of the body, while a second tester stood at the left side to ensure security. Then, hands were released and the child kept on walking independently for two additional minutes. After that, the speed of the belt was reduced to zero. This training protocol was repeated twice and subsequently two sequences for data analysis were registered with the 3D camera system. When the child was ready, the tester increased the speed gradually to the desired velocity. After approximately 30 s of walking steady state, a sequence of 10 s was registered by the camera system. One minute later, the walking belt was gradually stopped and after a short rest of 1 min a second sequence was recorded.

Data Processing

Following data collection, the three-dimensional trajectories were labeled and smoothed with a low-pass Butterworth filter at a cutoff frequency of 6 Hz. Next, the consecutive foot strikes (FS) and toe-offs (TO) from both feet were identified as the moments of maximal forward excursion of the ankle markers and the moment of maximal backward excursion of the toe markers. This method has been used previously by Donker, Beek, Wagenaar, and Mulder (2001). Eight consecutive strides, beginning with left FS and finishing FS of the ipsilateral foot of the second sequence were selected for further analyses.

Spatial step kinematics were calculated based on the location of the ankle marker. Step length was defined as the anterior-posterior distance from ankle to ankle at FS. The sum of two consecutive steps resulted in the stride length. Absolute step width was determined as the medio-lateral distance from right ankle to left ankle at FS. Since this distance is highly dependent on body morphology, step width ratio was calculated as the absolute step width divided by the medio-lateral distance between left and right trochanter major.

The temporal variables of interest were the total stride time (from FS to FS of the ipsilateral foot) which is divided in the support phase (from FS to TO of the ipsilateral foot) and the swing phase (from TO to FS of the ipsilateral foot). The support phase can be divided into an initial double support phase (from FS to opposite TO, i.e., TO of the contralateral foot), a single support phase which equals the swing phase of the contralateral foot (from opposite TO to opposite FS), and a second double support phase (from opposite FS to TO).

Segment angles of the foot, leg, thigh, and trunk were determined at critical moments in the gait cycle, at FS, opposite TO, opposite FS, and TO. According to Winter (1991), segment angles are defined as the angle between the frontal side of the segment and the horizontal. To facilitate the interpretation of the joint kinematics, relative joint angles of ankle, knee, and hip were also calculated. In Figure 1 the time course of these joint angles are displayed relative to the critical gait events.

The Index of Walking Performance was introduced by Woodruff et al. (2002) to compare the spatial-temporal pattern with that of a group of 139 children (3–7 years

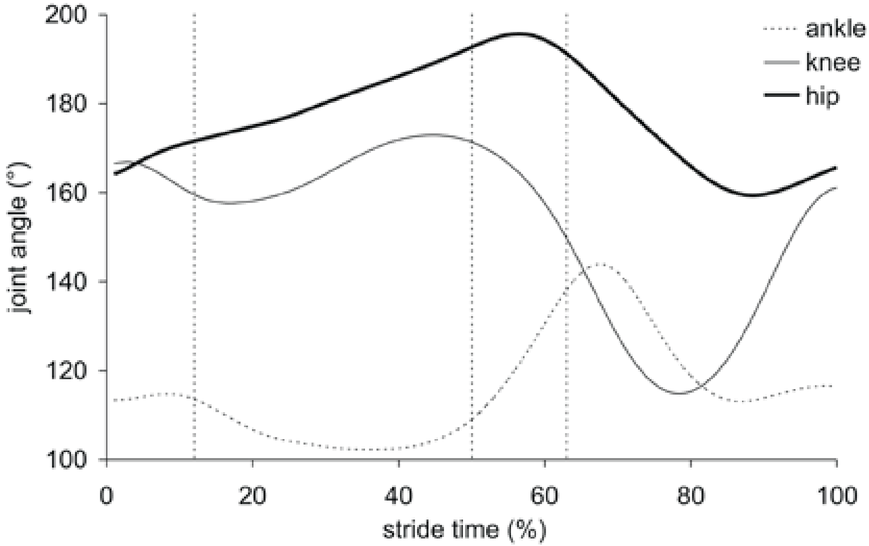

Figure 1—Typical time course of the joint angles of ankle, knee, and hip of a child (7.0 years old) relative to the total stride time expressed in percent. Broken vertical lines represent opposite TO, opposite foot strike, and TO, respectively.

of age) of the San Diego database (Sutherland et al. 1988). It is a one-dimensional measure of normality based on the occurrences of opposite toe-off, opposite foot strike, single stance, and step length all normalized to the duration or length of the gait cycle. Hotelling's T2 statistics and matrix calculations are used to combine the children's four scores into a single number. The cut-off value 2.69 was found to correspond to the 95th percentile and correspondingly all indices larger than 2.69 were classified as *abnormal*. See Woodruff et al. for a detailed description of the calculation of the Index of Walking Performance.

Statistical Analysis

A reliability analysis of the eight consecutive strides yielded an intra class coefficient above 0.85 for all dependent variables with the exception of the Index of Walking Performance (α = .74 for children with DCD and α = .77 for TD children). This allowed us to average the values of the eight consecutive strides of each individual to further investigate group differences (Portney & Watkins, 1993). The lower ICC for the Index of Walking Performance calls for caution when interpreting the analysis on the basis of the individual means. Because of the rigorous matching procedure the two groups of children could not be considered independent and differences between TD children and children with DCD were evaluated with a paired sample *t*-test for each dependent variable. Alpha level for statistical significance was set at .05. Cohen's *d* was calculated to measure effect sizes.

Results

The temporal phasing of the gait cycle is shown in Figure 2. Differences between children with and without DCD were found for all absolute temporal variables. Stride time of children with DCD was significantly shorter, $t(9) = 3.019$, $p < .05$, $d = 1.752$, which was attributed to both a shorter support, $t(9) = 3.260$, $p < .05$, $d = 1.161$, and a shorter swing phase, $t(9) = 2.377$, $p < .05$, $d = 2.013$. Children with DCD also spent less time in double support, $t(9) = 2.578$, $p < .05$, $d = 1.202$. However, when these temporal measures were scaled to the duration of the entire gait cycle all differences disappeared, indicating that the relative phasing of the walking pattern of both groups was similar (see Figure 2). As shown in Table 2, the shorter stride time of the children with DCD resulted in a significantly higher cadence, $t(9) = 2.849$, $p < .05$, $d = 2.079$. The stride length of children with DCD was shorter, $t(9) = 2.408$, $p < .05$, $d = 1.205$, but neither step width or step width ratio differed between groups.

Table 3 displays the segment angles at initial FS, opposite TO, opposite FS, and TO. Body kinematics throughout the gait cycle differed mainly at the level of the trunk. In children with DCD, the trunk was inclined more to the horizontal at initial FS, $t(9) = 2.540$, $p < .05$, $d = 1.690$, opposite TO, $t(9) = 2.502$, $p < .05$,

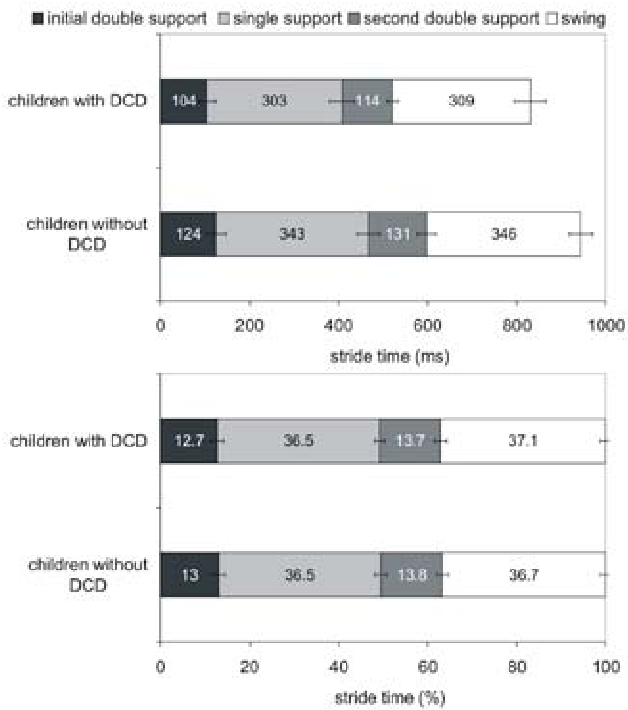

Figure 2—Temporal gait parameters of children with and without DCD. Error bars indicate the standard deviations. Absolute values are displayed in the upper panel, values relative to the total stride time are shown in the lower panel

Table 2 Means of Means and Standard Deviations for the Gait Parameters

	Children with DCD		Children without DCD	
Variable	*M*	*SD*	*M*	*SD*
Stride length (mm)	711*	84.5	799*	101.0
Absolute step width (mm)	146	15.6	141	15.5
Step width ratio	0.63	0.097	0.57	0.086
Cadence (steps/min)	146*	16.4	128*	16.9
Index of walking performance	4.36*	3.148	1.28*	0.743

* $p < .0$

Table 3 Means of Means and Standard Deviations for the Segment Angles

Angle	Group		FS	Opposite TO	Opposite FS	TO
foot (°)	children with DCD	*M*	169.0	161.9	144.4	109.6*
		SD	6.86	3.76	5.60	7.39
	children without DCD	*M*	172.7	161.2	141.1	101.0*
		SD	6.65	3.68	9.23	5.97
leg (°)	children with DCD	*M*	97.1*	83.4	63.6	43.2
		SD	3.68	2.84	3.13	3.41
	children without DCD	*M*	101.2*	86.6	63.4	42.3
		SD	4.73	5.17	6.69	3.99
thigh (°)	children with DCD	*M*	117.9*	112.3*	83.2	90.5*
		SD	2.16	2.59	4.34	3.99
	children without DCD	*M*	115.0*	108.6*	78.9	85.6*
		SD	3.57	3.80	5.84	5.85
trunk (°)	children with DCD	*M*	82.3*	83.7*	76.2*	79.1*
		SD	6.42	6.76	5.14	5.36
	children without DCD	*M*	89.2*	90.9*	83.1*	85.0*
		SD	5.79	6.35	5.65	5.51

Note. FS = foot strike, TO = toe-off; * $p < .05$.

$d = 1.608$, opposite FS, $t(9) = 2.872$, $p < .05$, $d = 1.722$,and TO, $t(9) = 2.374$, $p < .05$, $d = 1.516$. At FS, leg angle was slightly more flexed in the children with DCD, $t(9) = 2.324$, $p < .05$, $d = 1.226$, and the angle of the thigh was more in anteversion, $t(9) = 2.505$, $p < .05$, $d = 1.169$. The thigh still was more flexed at opposite TO, $t(9) = 2.625$, $p < .05$, $d = 1.377$, and at TO, $t(9) = 2.377$, $p < .05$, $d = 1.184$. At TO, the foot of children with DCD was less in plantar flexion than that of the typically developing children, $t(9) = 3.547$, $p < .05$, $d = 2.037$.

In Table 4 it can be observed that this pattern of segment angles resulted in several differences at the level of the joint angles. At FS the angles of the knee and hip were significantly more flexed in children with DCD, $t(9) = 3.546$, $p < .05$, $d = 1.606$ and $t(9) = 4.141$, $p < .05$, $d = 2.198$ for knee and hip, respectively. The knee angle still was smaller at opposite TO, $t(9) = 2.302$, $p < .05$, $d = 1.316$, while hip angle remained more flexed during the entire time course (at opposite TO: $t(9) = 3.375$, $p < .05$, $d = 1.919$, at opposite FS: $t(9) = 3.671$, $p < .05$, $d = 2.456$, and at TO: $t(9) = 3.451$, $p < .05$, $d = 2.243$). The ankle was found to be significantly less extended in children with DCD at TO, $t(9) = 2.806$, $p < .05$, $d = 1.650$. Joint kinematics at initial foot strike (FS) and at toe-off (TO) are illustrated by the stick figures in Figure 3.

The mean Index of Walking Performance was significantly larger, i.e., worse, for the children with DCD compared to the typically developing children, $t(9) = 2.759$, $p < .05$, $d = 5.849$ (Table 2). Moreover, the mean index of the DCD group fell in the abnormal range (> 2.69). Conversely, the mean of the TD group did not

Table 4 Means of Means and Standard Deviations for the Joint Angles

Angle	Group		FS	Opposite TO	Opposite FS	TO
ankle (°)	children with DCD	*M*	108.0	101.4	99.0	113.4*
		SD	4.86	4.40	4.45	5.78
	children without DCD	*M*	109.5	105.5	102.3	121.3*
		SD	4.37	4.48	4.31	6.77
knee (°)	children with DCD	*M*	159.1**	151.0*	160.4	132.7
		SD	4.67	4.60	6.07	4.27
	children without DCD	*M*	166.4**	158.1*	164.5	136.7
		SD	6.43	7.63	11.88	9.10
hip (°)	children with DCD	*M*	144.4**	151.2**	172.6**	168.5**
		SD	7.15	7.65	8.89	8.74
	children without DCD	*M*	154.3**	162.3**	184.3**	179.4**
		SD	6.01	7.57	6.30	6.42

Note. FS = foot strike, TO = toe-off;* $p < .05$; ** $p < .01$

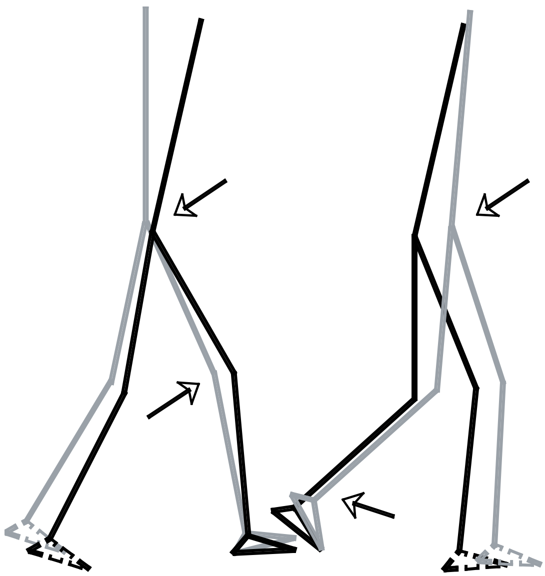

Figure 3—Stick figures of the body configuration at initial FS (left) and TO (right). Grey lines represent the TD children without DCD, black lines represent the children with DCD. Feet with broken lines are the contralateral feet. Arrows indicate significant differences of the joint angles ($p < .05$)

reach abnormal values. Figure 4 illustrates the stride by stride Indices of Walking Performance for each individual child. Close observation indicates that 6 out of 10 children with DCD had a mean index larger than 2.69, while this was the case in none of the TD children. Out of 80 strides covered by the children with DCD, 35 (43.75%) were above 2.69, compared to only 7 (8.75%) for the TD children. This diagram further indicates that both inter- and intra-variability were distinctly larger in children with DCD. Statistical analysis of the standard deviations of the individuals' means revealed that this difference was significant, $t(9) = 3.573$, $p < .05$, $d = 5.982$.

Discussion

The present study attempted to identify if and how the gait pattern of children with DCD differed from that of their typically developing peers. In accordance with Woodruff et al. (2002), it was found that children with DCD had significantly more Indices of Walking Performance above the cut-off point, indicating aberrant walking behavior. Whereas each child with DCD displayed at least one stride with an index in the abnormal range, four had a mean index below the cut-off value. This lack of consistency together with the limited explanatory power of a one-dimensional index with regard to potential underlying factors of the deviant walking pattern suggests the need for a more detailed gait analysis.

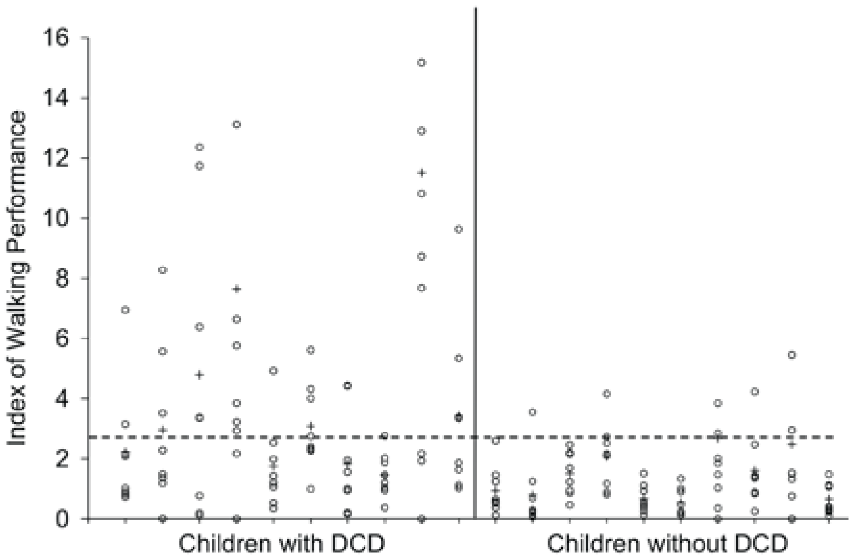

Figure 4—Index of Walking Performance for the 10 children with and the 10 children without DCD. Values of the separate strides are indicated with ○, means per child are indicated with +. The horizontal broken line indicates the cut-off value (2.69) according to Woodruff et al. (2002).

Based on the four spatio-temporal gait parameters that are part of the index, Woodruff et al. (2002) could not find differences between 6 year-old children with DCD and the 3–7 year-old reference population of Sutherland et al. (1988). Conversely, in the present study, where the typically developing children were rigorously matched to the children with DCD, it was found that the latter displayed a gait pattern with shorter strides in both time and space, while stepping at a higher frequency than their typically developing peers. When scaled to the total gait cycle duration, the reduction of the separate gait phases did not imply a distortion of the relative phasing, indicating that children with DCD did succeed in establishing a normal and rhythmic locomotor pattern, although shortened in time and space. In addition, the trunk of children with DCD was inclined more towards the ground and they displayed increased knee flexion at initial foot contact and less plantar flexion at toe-off.

A temporal and spatial shortening of the gait cycle is a strategy that is also adopted by new walkers (Sutherland et al., 1988). In children with DCD these adaptations were accompanied by other changes indicative of an immature gait pattern like the propensity to place the foot flatter at initial contact and the less pronounced toe-off of children with DCD. However, while several gait characteristics of children with DCD may have similarities with a less mature gait pattern, this does not necessarily imply that with further maturation children with DCD will overcome their problems. Previous research has shown that children with DCD do not spontaneously recover from their coordination problems (Henderson & Barnett, 1998). Therefore, an alternative explanation is that the similarities with immature gait result from reactions to a primary impairment which appears to force the children with DCD, like new walkers, to adopt a safer walking strategy. Extensive study on the onset and the development of walking has pointed towards the primary role of force and posture (Adolph, Vereijken, & Shrout, 2003; Clark & Phillips, 1993; Thelen, 1986). The ability to hold the body upright while propelling it forward and catching it at contact depends on both strength in the leg muscles and postural control. The causes for the conservative walking strategy displayed by children with DCD may be sought in that direction.

In this context, the shorter time spent in single support by children with DCD might be a reflection of diminished neuromuscular maturity and limb instability as proposed by Sutherland et al. (1988). The ability to support the body on one leg largely depends on the strength of the supporting leg. Likewise, the less pronounced plantar flexion preceding toe-off can be an expression of lack of strength to propel the body forward. A decrease of the ankle plantar flexion during terminal stance will likely reflect a decrease in ankle plantar flexion torque, which is responsible for the most important energy generation phase of the gait cycle (Winter, 1991). In sum, these differences may be a kinematic manifestation of the neuromuscular problems that have been found to occur in children with DCD (Raynor, 2001). However, further kinetic and EMG analysis is warranted to investigate the extent of these problems in walking.

As in the elderly, the walking pattern of children with DCD might also be a protective adaptation to a perceived threat to stability (Menz, Lord, St George, & Fitzpatrick, 2004). Anticipatory and reactive postural control of children with DCD in response to perturbations in static conditions has been shown to be less accurate and efficient (Johnston, Burns, Brauer, & Richardson, 2002; Williams, 2002). As a result, the less pronounced plantar flexion preceding toe-off and the correspondingly smaller steps, may be interpreted as a strategy to produce a smaller destabilizing momentum at toe-off, *just* before the body initiates the most unstable phase. Therefore, the gait adaptations of children with DCD could be viewed as different control patterns stemming from altered central nervous system considerations in response to perceived threats to balance or postural control, as suggested by Latash and Anson (1996).

Another balance-related gait parameter is the placement of the foot relative to the center of mass, expressed as the step width (MacKinnon & Winter, 1993). Populations with balance problems often show an increase of the step width to conquer destabilizing torques in the frontal plane (Sutherland et al., 1978 & 1988). In the present study, absolute step widths of both groups (146 ± 15.6 mm for children with DCD and 141 ± 15.5 mm for TD children) are large compared to reference values for treadmill walking available in the literature (106 ± 23.2 for children age 6.6 years in Stolze et al., 1997). This might suggest an increase of the base of support, although no differences were found between the children with and without DCD.

However, it appears that children with DCD adapt their walking pattern at another level to meet the balance requirements. The enhanced forward inclination of the trunk with correspondingly smaller hip angles over the entire gait cycle and increased knee flexion during stance, result in a lowering of the center of mass (see Figure 3). This implies that the destabilizing effect of the gravitational torque about the supporting foot decreases (MacKinnon & Winter, 1993). With these kinematic accommodations, children with DCD reduce the stability constraints on walking which might make additional adaptations such as wider foot placement unnecessary.

The balance problems experienced while walking on a treadmill may be partially related to the peculiarities of the task itself. As reported in several studies that compare treadmill and overground walking, factors such as the change of afferent sensory input or the work transferred between the subject and the treadmill may also have influenced the walking pattern in the present study (Savelberg, Vorstenbosch, Kamman, van de Weijer, & Schambardt, 1998; Stolze et al., 1997; Wall & Charteris, 1981). Indeed, in correspondence with previous findings, our results suggest that cadence tended to be higher and step length appeared to be shorter than in overground walking. Nevertheless, treadmill walk testing is found to be appropriate for group comparison when similar conditions are used, although some caution is warranted when interpreting the results and extrapolating the findings to overground walking (Alton, Baldey, Caplan, & Morrissey, 1998).

In this context, the influence of the visual flow pattern on the gait parameters is of particular interest (Prokop, Schubert, & Berger, 1997). Treadmill walking offers a unique situation where visual flow remains virtually absent. From various accounts it can be acknowledged that children with DCD have an increased dependency on visual information and cannot tune inflow of proprioceptive, visual, and vestibular information to the environment as adequately as children without coordination problems (Wilson & McKenzie, 1998). Moreover, children with DCD were shown to experience more harm in situations with conflicting sensory modalities for maintaining balance (Deconinck et al., submitted; Wann et al., 1998). Therefore it can be assumed that the children with DCD in this study were more susceptible to sensory conflict between the lack of visual flow and the vestibular and proprioceptive input related to treadmill walking than TD children. As a consequence, the sensory integration deficits of children with DCD may also be part of the explanation of their different gait pattern on the treadmill.

In general, children with DCD appear to experience more problems finding the optimal compromise between forward propulsion and dynamic stability while walking on a treadmill. Even though the picture of the Index of Walking Performance appears to contradict this view on some occasions, a careful look into its spatiotemporal components, together with analysis of other kinematic parameters helps to better comprehend the nature of the walking pattern of children with DCD. To illustrate this, a single-subject analysis of the four children with DCD who had an index in the normal range (DCD1, DCD5, DCD7, and DCD8) was carried out. From Figure 5, which presents the individual results for the spatiotemporal variables that discriminated between the groups with and without DCD, it is clear that DCD5 and DCD8 tend towards the mean of the children with DCD. The spatiotemporal variables of DCD1 and DCD7, however, approximated the means of the children without DCD. While spatiotemporal adaptations of the gait pattern in these children appeared to remain absent, their joint angles at critical moments of the gait cycle clearly showed deviations in the direction of the children with DCD (see Table 5). Similar findings were noticed for DCD5, but adaptations to the joint angles were virtually absent in DCD8. Overall, these single-subject results indicate that all children with DCD who obtained index values in the normal range displayed adaptations to the gait pattern at one or another level. Consequently, a "normal" Index of Walking Performance can be the result of a complex of successful adaptations to the gait pattern.

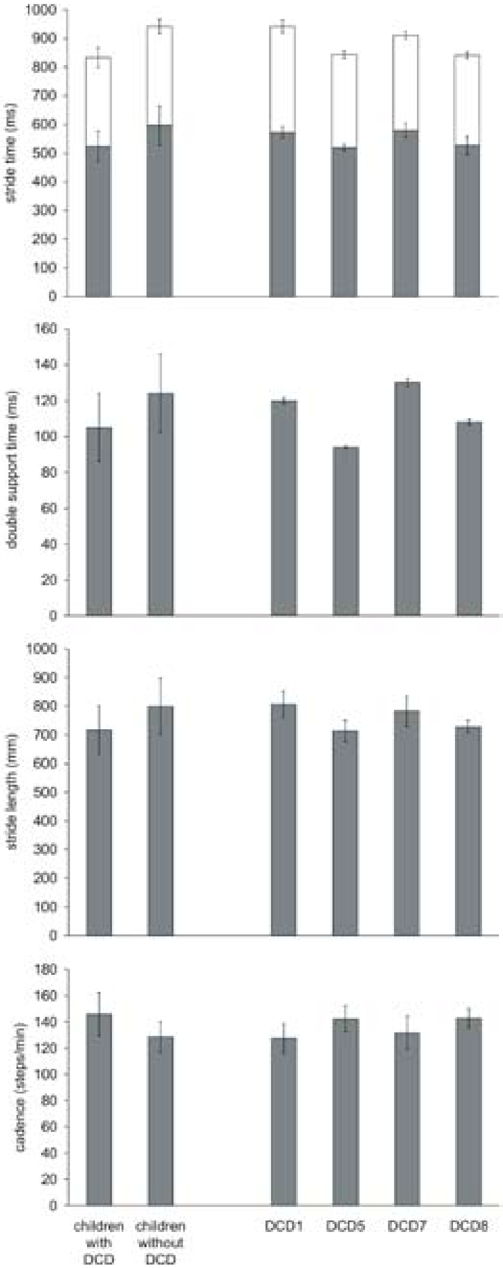

Figure 5—Stride time, double support time, stride length, and cadence for the children with DCD, with an Index of Walking Performance above the cut-off value in comparison with the means per group. Error bars indicate the standard deviations. Stride time is divided into support phase (grey bar) and swing phase (white bar).

In summary, the gait pattern of children with DCD was studied by means of spatiotemporal and kinematic joint variables and revealed distinct differences with typically developing children. When walking on a treadmill at a similar scaled velocity the gait cycle of children with DCD was shorter in time and space which resulted in a higher cadence. In addition, the body configuration of children with DCD appeared to be more bent than in their typically developing peers. The differences found might be interpreted as the kinematic outcome of accommodations caused by problems at the neuromuscular or postural control level, and in this sense the gait pattern of children with DCD should be considered adaptive rather than abnormal. While this ensemble of adaptations may not always be present in each individual child with DCD, one or another kind of adjustment was present in all of them. The present results indicate that even a fairly easy locomotor task can challenge children with DCD. Whereas they seem to have found strategies to cope with their movement difficulties in a structured, uncluttered environment, it might be clear that these strategies could fail in daily living or sport situations.

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